

Radiation Tolerance Assurance for ATLAS CSC Electronics

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1 Introduction

The ATLAS Cathode Strip Chamber (CSC) on detector electronics will be running in a highly radiating environment. The radiation mainly from neutrons and photons may inflict damage to the electronic system and jeopardize normal data acquisition or in some serious case cause fire on circuit boards. Therefore for the safety of the persons operating the experiment and the safety of the detector, it is highly desirable to have radiation tolerance assurance for all the electronic devices mounted on detector.

2 Radiation environment at the location of CSC

The radiation levels at the location of CSCs have been computed using the ATLAS Monte Carlo simulation. Assuming 180 days of ATLAS operation annually, at the worst location for radiation, the ionizing dose from photons reaches 1.1 KRad/yr (Si) and the neutron flux reaches 7.0×10^{12} neutrons/cm²/yr which

Table 1: Neutron flux and energy spectrum at the location of Cathode Strip Chamber

Neutron Energy Range	Worst Location (KHz/cm ²)	Best Location (KHz/cm ²)
0 ~ 1 KeV	100	20
1 ~ 10 KeV	100	10
10 ~ 100 KeV	100	10
100 KeV ~ 1 MeV	100	10
1 ~ 10 MeV	20	5
10 ~ 100 MeV	10	1
100 MeV ~ 1 GeV	5	1
Total	450	50

converts to 1.8×10^{12} 1-MeV-equivalent neutrons per square centimeter per year. At the best location, the radiation levels are an order of magnitude lower. Table 1 lists the detailed neutron flux and energy spectrum at the best and worst locations for radiation of the Cathode Strip Chamber. The worst location for radiation occurs at R= 89 mm, and Z = 725 mm; and the best location is at R= 197 mm, and Z = 690 mm.

3 Radiation effects to electronic components

The damages caused by neutron and photon radiations to electronic devices can be grouped into three categories based on their damaging mechanisms:

- **Total Ionizing Dose Effects** induced by photons. Photon causes ionization (electron-hole pair production) along its track in Si or SiO₂. Because of their high mobility, electrons will drift out of the oxide layer quickly. Meanwhile the holes produced in the ionization processes have very low mobility, most of them will be trapped in the oxide. The effect is that there is net positive charge trapped in the oxide layer in silicon devices. Especially at room temperature, the trapping is long term. The positive charge accumulated in the oxide layer will cause noise increase and electric parameter drifting out of its dynamic range hence claim the death of a silicon device.
- **Displacement Damage** caused by non-ionizing energy loss of heavy particles such as neutrons or protons in materials. Neutrons or protons collide with the atoms in material inducing dislocation of atoms or amorphization of the material structure. In silicon devices, the effective majority carrier concentration decreases due to displacement damage which effectively increases the resistivity of the material. Severe displacement damage could induce type inversion of silicon for example N → P, hence cause the dysfunction of a device
- **Single Event Effects** induced by single energetic heavy particles such as neutrons or protons passing through Si or SiO₂. Most of the neutrons pass through materials by elastic scattering or diffraction and inflict displacement effect, but when neutron energy is greater than an energy threshold, nuclear reactions such as $n + \text{Si} \rightarrow p + \text{Al}$ and $n + \text{Si} \rightarrow \alpha + \text{Mg}$ start to come on to the stage to play an important role. The secondary charged ions produced in nuclear reactions will produce further ionization along its track. The charges along the track cause a transient current which, if big enough, enables digital flip-flops to change state, therefore induce data corruption. This phenomenon is called “Single Event Effects”. The Single Event Effects can be categorized into three classes based on the degree of the radiation damage to the electronics devices
 1. Single Event Upset, the upset is transient; a reset or rewrite of the device will restore normal behavior thereafter.

2. Single Hard Error, an upset causes permanent change to the operation of a device, for example, a stuck bit in memory chip.
3. Single Event Latchup/Burnout/Gate Rupture (destructive), very high current in a local area causes neighboring gates latchup or chemical bonds rupture or gates burnout.

There have been a number of studies on the soft error rates (Single Event Upset). Studies show that the SEU cross sections have the same sensitivity to neutrons and protons when the energy of the particles is higher than 20 MeV and the SEU cross section has a flat distribution with respect to the neutron energy. In ATLAS environment, the SEU errors induced by neutrons with $E < 20$ MeV only account for less than 10% of the total soft Single Event Upsets. It is more significant and reasonable to test the Single Event Upset error rate with a higher energy proton beam. ATLAS recommended the proton energy should be in the range 60 to 200 MeV.

The destructive Single Event Effect is the most severe and dangerous damage a heavy particle could induce to an electronic device. Up-to-date, no study has been conducted to estimate the rates of Single Hard Error and destructive SEEs. However it is clear that the production of hard and destructive SEEs requires a high local instantaneous energy deposition (much higher than that required for producing soft SEUs). In HEP experiments like ATLAS, particles with a high linear energy transfer are produced by fission reactions induced by energetic hadrons on elements heavier than 170-180 AMU. It is estimated that most of the fission reactions can be triggered by 500 MeV protons. A proton beam with the energy 500 MeV or above can be used to test the hard and destructive SEEs.

4 Radiation Tolerance Criteria

ATLAS electronic components must have radiation tolerance equal to or higher than minimum values called Radiation Tolerance Criteria (RTC) of 10 years of LHC operation. The RTCs for Total Ionizing Dose (TID) and Displacement Damage (Non-Ionizing Energy Loss/NIEL) are defined as following:

- $RTC_{TID} = SRL_{TID} SF_{sim} SF_{LDR} SF_{lot}$ (unit: rad/yr),
- $RTC_{NIEL} = SRL_{NIEL} SF_{sim} SF_{LDR} SF_{lot}$ (unit: 1-MeV-equivalent neutrons/cm²/yr).

where the SRL stands for the Simulated Radiation Level which is introduced in section 2. Table 2 lists the safety factors for various concerns.

The RTCs for Single Event Effects are the SEE error rate. The values have to be defined by each detector system based on an acceptable data loss rate. The radiation tolerance criteria for the CSC system will be discussed in the next section.

Table 2: Safety Factors defined by ATLAS Radiation Tolerance Assurance Group.

Parameter	Description	TID	NIEL
SF _{sim}	Safety Factor for Simulation	4	4
SF _{LDR}	Safety Factor for Low Dose Rate	5	1
SF _{lot}	Safety Factor for unknown lots	4	4

5 Radiation Tolerance Criteria for Single Event Upset

There is no ATLAS-wide Radiation Tolerance Criteria for the Single Event Upset rate up-to-date. For the on detector electronics of Cathode Strip Chamber, we have adopted an in-efficiency of 0.1% for the whole CSC system due to Single Event Upsets. The number is ignorable compared to the in-efficiencies due to other factors. To obtain an acceptable upset rate for a single G-Link chip, we calculate the error rate standard as shown in table 3 based on the test of the G-Link transmitter by the ATLAS Liquid Argon group.

Table 3: Radiation Tolerance Criteria for SEU

Parameter	value	Comment
CSC system in-efficiency	0.1%	In-efficiency is defined as 100% - efficiency
In-efficiency per G-Link	0.78×10^{-6}	1280 weighted G-links for the CSCs [†]
Link-down time	1 ms	1 ms to recover a link down.
No. of chips per link	2	transmitter and receiver
Data dropped after recovery	8 triggers	8 triggers worth of data will be dropped to flush the garbled charges due to the link down.
Link down probability per SEU	100%	Although not every SEU causes link-down, link-down certainly will introduce more problem. To set a safe SEU rate, we assume the worst for each SEU occurrence.
Acceptable SEU rate	one SEU per 43 minutes per chip	A factor of 5 has to be considered to account for the uncertainty in neutron flux simulation.

[†] The total number of G-Links on detector is 960. 2/3 of them are transmitters and 1/3 of them are receivers. When one receiver link is down, because it is carrying control signals, the two transmitter links on the same ASM board will not transmit any data, so the data loss will be twice as much as when the

transmitter link is down. We give a weight of 2 to the receiver links and a weight of 1 to the transmitter links. Therefore the total weighted G-Links on detector is 1280.

6 Irradiation Test Methods

- TID test method for the qualification of CMOS/bipolar/BiCMOS lots
 1. Selection of a calibrated ionizing dose facility (Gamma or X-ray);
 2. Selection of a set of 11 good devices (for a known lot) or 22 good devices (for unknown lot);
 3. Number all devices;
 4. Electrical measurement of all devices at room temperature;
 5. Random selection of 1 device among the set of 11 (or 2 among the set of 22). The selected devices will not be irradiated and will serve as the reference.
 6. Irradiation of the 10 (Or 20) other devices at room temperature under bias in one or several steps up to the RTC required for CSC.
 7. Electrical measurements at room temperature; rejection of the lot if one of the 10 (or 20) fails;
 8. Annealing of CMOS devices under bias 168 hours at room temperature; rejection of the lot if one device fails;
 9. Documentation of the test result.
- Displacement Damage (NIEL) test method – any device except pure CMOS devices (pure CMOS devices are naturally tolerant to displacement damage).
 1. Selection of a calibrated neutron facility (1-MeV-equivalent neutrons/cm²).
 2. Selection of a set of 11 good devices (for a known lot) or 22 good devices (for unknown lots);
 3. Number all devices;
 4. Electrical measurement on each device at room temperature;
 5. Random selection of 1 device among the 11 or 2 devices among the 22 as the reference; the Selected device(s) will not be irradiated.
 6. Irradiation of the rest 10 (or 20) devices up to the RTC at CSC; During irradiation, all the leads of each device must be shortened together;
 7. Electrical measurement on each irradiated device at room temperature plus inspection of any damage after deactivation.
 8. Rejection of the generic component if any of the 10 (or 20) irradiated devices fails.

9. Documentation of test result.
- Single Event Effect(SEE) test method – based on proton beam
 1. Selection of a calibrated proton facility, 60 MeV proton beam for soft SEE test only or >500 MeV proton beam for global SEE test including soft, hard and destructive SEEs.
 2. Selection of a set of 4 good devices from unknown lots.
 3. Number all devices.
 4. Electrical measurements on each device at room temperature (pre-irradiation, check whether on-line monitoring is working properly).
 5. Irradiation of each device at a controlled temperature with a constant proton flux, up to a total fluence large enough to produce an accurate measurement of the SEE rate. During irradiation: on-line electrical operation and measurement.
 6. After irradiation, inspection for destructive damage.
 7. Computation of the soft, hard and destructive SEE rates expected in the ATLAS CSC location.
 8. Documentation of the test result.

7 Electronics devices to be tested for radiation tolerance

Electronic devices mounted on the CSC detector will have to be qualified for radiation tolerance of 10 years of operation. Table 4 lists the devices to be tested.

Table 4: CSC on detector electronics devices to be tested for radiation tolerance.

Component	Function
HDMP 1022	G-Link transmitter
HDMP 1024	G-Link receiver
SCA	Switched-Capacitor Array
AD9042	Analog Digital Converter
AD8042	Op-Amp
DAC	Digital Analog Converter
Level Translators	Translator between different logics
Readout interface IC	

8 Irradiation facilities

We have established that the following facilities are suitable for the radiation tolerance assurance tests:

1. The ^{60}Co source at Gamma Irradiation Service at the University of Michigan provides a peak gamma rate of 2 Mrad/hour at the center. This source can be used for the total ionizing dose effect test. Approximately 15 minutes of irradiation will be needed at this source or longer time if the devices under test are irradiated at a lower gamma rate.
2. Nuclear reactor at University of Rhode Island provides 1-MeV-equivalent neutrons at a flux of 4×10^{12} neutrons/cm².s. Using this facility, 75 seconds of irradiation will be able to qualify or disqualify a device for the displacement damage effect.
3. Crocker Cyclotron at University of California, Davis provides 63 MeV proton beam. The beam flux can be tuned in the range $3 \times 10^5 \sim 2 \times 10^{10}$ protons/cm².s. This facility can be used to test the Single Event Upset.
4. Neutron Science Center at Los Alamos National Laboratory provides 800 MeV proton beam at a maximum flux of 3×10^{12} protons/cm².s. This source can be used to test the Single Hard Error, Latchup, Gate Rupture and Burnout. Any of these errors will disqualify a device.

The radiation tolerance of the electronics devices has to be studied very carefully to assure the success of the whole data acquisition system for the Cathode Strip Chamber.